COMPARATIVE COGNITIVE REACTION-TIME WITH LIGHTS OF DIFFERENT SPECTRAL CHARACTER AND AT DIFFERENT INTENSITIES OF ILLUMINATION

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Introduction

Previous to the beginning of the present century all light used for purposes of general illumination was produced from incandescent solids, and hence possessed a continuous spectrum, of the same order as the solar spectrum, but differing in that it contained relatively less energy in the shorter wave-lengths, and more in the longer. The effect of monochromatic light, or of light possessing a line spectrum, on cognitive reaction-time was therefore a problem of pure science, and does not appear to have been investigated. (For the sake of brevity, the term "reaction-time" will be used henceforth, the words "visual cognitive" being understood.)

Early in this century Peter Cooper Hewitt discovered and developed a practical method of producing light from incandescent mercury vapor. Light so produced possesses the characteristic line-spectrum of mercury, in which a band in the greenish-yellow largely predominates, rendering it approximately monochromatic. As this light-source has come into general use for industrial purposes, the question of the effect of such light upon reaction-time becomes a matter of interest to applied, as well as to pure science. The present investigation was undertaken with a view to ascertaining what differences, if any, in such reaction-time would result from the use of light from mercury vapor, incandescent tungsten, and the sun under average conditions of daylight.

Spectral Character of the Different Kinds of Light Used

Mercury vapor light differs widely from the other two, its spectrum consisting essentially of four lines, *viz.*, a strong pair of greenish-yellow wave-lengths 579 $\mu\mu$ and 577 $\mu\mu$, an extremely brilliant green line of wave-length 546 $\mu\mu$, and a brilliant deep-

blue line of wave-length 436 $\mu\mu$. In addition to these there is a very faint crimson line, a faint blue-green line, and a pair of weak lines in the far violet. According to Bell's measurements,[1] about 90% of the visible energy of mercury vapor light is due to the three bands close together in the greenish-yellow and green, the balance being due to the blue line. This combination gives the light its peculiar "peacock blue" color.

Light from incandescent tungsten possesses a continuous spectrum somewhat richer in the red, orange and yellow, and weaker in the blue and violet, than sunlight. The curve, Fig. 1,

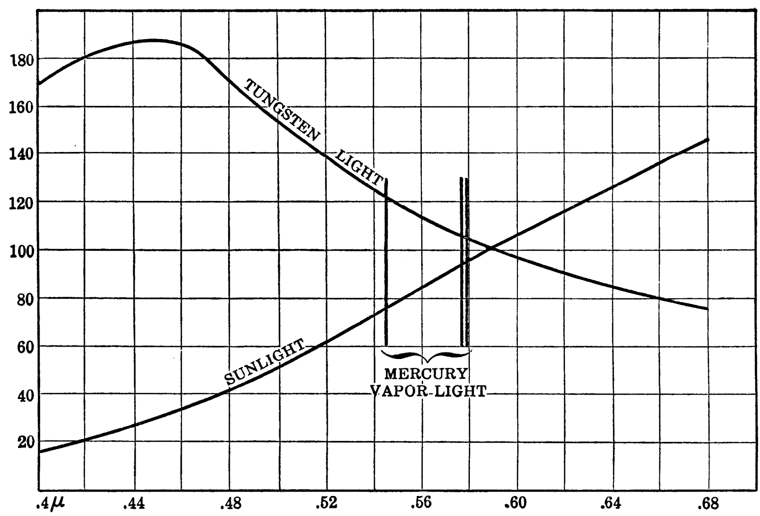


FIG. 1

shows the relative distribution of radiant energy in the spectra of blue sky, and the gas-filled tungsten lamp, equated to equal total visual intensity, *i. e.*, with 590$\mu\mu$ taken as 100 for each light, according to Luckiesh[2]. The vertical lines show the position of the three principal bands of the mercury spectrum.

Chromatic Aberration and Visual Acuity

In the early part of the nineteenth century Wollaston[3] showed that the refractive system of the eye is not achromatic, as had previously been assumed, but is slightly dispersive. Bell[4] states that "it is only in virtue of a very high maximum point in the luminosity curve of the eye that we are able to see distinctly at all. And it is this same fact which prevents the chromatic aberration being conspicuous under ordinary circumstances." This matter has recently been very carefully investigated by

Hartridge.[5] He finds that the relative dispersion of the refractive system of the eye is 45, which corresponds to that of a light flint glass.

The fact that the eye is subject to chromatic aberration naturally suggests the supposition that monochromatic light, by eliminating this optical defect, may increase visual acuity, or resolving power. This hypothesis has been investigated by Uhthoff[6], König[7], Orum[8], Broca and Laport[9], Ashe[10], Dow[11], Bell[12], Luckeish[13] and Rice[14]. There is a wide disparity in the conclusions reached by these investigators, which evidently arises from the difference in the method and apparatus used. Bell and Luckiesh used the same general methods, which consisted essentially in determining the relative intensities of illumination, measured on an equality of brightness scale, of light of different spectral character necessary to enable the eye to resolve certain test objects. Their conclusions are in very close accord, and show that the ratio of intensity of illumination by incandescent electric light to that of mercury vapor light, to produce equal acuity, or resolving power, is as 1.75 to 1, at ordinary intensities (1.5 to 2 foot-candles). Since it is well known that acuity is a function of illumination intensity, or surface brightness of the object, these results establish the fact that monochromatic light, or light of simple spectral character, gives greater acuity of vision than continuous spectra light.

Objects of the Present Investigation

Visual acuity being a function of the spectral character of the light, the further question suggests itself, whether reaction-time may not also vary with the nature of the light. The present investigation seeks to solve two related problems, *viz.*,

(1) What is the effect of light of different spectral character upon cognitive reaction-time?

(2) What is the effect upon cognitive reaction-time of different intensities of illumination?

As before suggested, these problems have a direct bearing upon manual labor performed under the direction of vision, since all such labor consists of muscular reactions in response to visual impressions in which cognition plays an important part. In devising the experiments, therefore, care was taken to insure actual cognition at each observation, and to eliminate the elements of visual resolution, practice, and fatigue.

Nature of the Experiments

The experiments consisted in exposing a test-object through an opening in the shutter, illuminated under given conditions, and requiring the observer to register his cognition of the object by pressing an electric key. The time required for the cognition and muscular reaction was recorded by a chronograph.

Apparatus

A special apparatus was constructed for carrying out the experiments. This consisted of a board 10x15 in., through the center of which was an opening 3/8x7/8 in., the whole being covered with neutral gray paper, and supported at an angle of 45° upon a baseboard. A shutter of gray cardboard, in which there was an opening slightly smaller than the opening in the board, was attached by a pivot to the underside in such a manner that the opening would register with the opening in the board. This shutter was actuated by a spring, and its motion controlled by two stops operated by electromagnets connected in series with two electric keys located on diagonally opposite corners of the baseboard. Each of these keys was also in series with a pen on the chronograph.

The test-objects consisted of numbers containing 4 digits, printed in 10-point Roman type on white bond paper in black carbon ink. 120 different numbers were printed on a tape of paper, and means were provided for passing this tape immediately back of the shutter, so that when the two openings registered one of the numbers was exposed to view. A duplicate set of numbers was also typed upon one side of the tape, which did not appear to the observer, but which registered with an opening visible only to the operator, thus showing to the operator the number presented to the observer.

A Gaertner chronograph was used, so geared that 1 sec. of time represented a distance of slightly more than 1 in. on the record. Two pens were provided, one of which was in series with the shutter magnets, as described, and the other in series with a clock pendulum which made electric contact through a mercury globule at each oscillation. The rate of vibration of the pendulum was determined by taking a chronograph record of its oscillations for 10 min., timed by a stop-watch, and dividing the total time by the number of recorded oscillations. The electric current for operating the electromagnets was supplied by 4 dry cells.

Sources of Light

The light used to illuminate the test-object was from three different sources; *viz.*,

A Cooper Hewitt mercury vapor lamp, Type F, operated on alternating current, 60 cycles, at 4 amps, and 100 volts at the terminals, the line voltage being reduced somewhat by the resistance used to maintain constant curent.

Two tungsten filament, gas filled, incandescent electric lamps, of 200 watts and 300 watts rated capacity respectively, at 105 volts. The lamp-bulbs were fitted with "cap diffusers," *i. e.*, hemispherical specular reflectors which covered the lower part of the bulb, and projected the reflected light on to the white enameled still reflector, known in the trade as the "R. L.

M.," which was used with the lamps. The Cooper Hewitt lamp was equipped with the standard white enameled reflector supplied by the manufacturers.

Diffused sunlight admitted through one or two windows.

The wattage of the lamps was kept constant by the use of a rheostat, which was adjusted in accordance with the indications of a voltmeter in the case of the tungsten lamp, and an ammeter for the Cooper Hewitt lamp.

The room used for the experiments was 16 ft. square, with 10 ft. 6 in. ceiling, and had windows in the center of two adjacent sides, facing east and south, extending 10 in. from the ceiling. Each of the other sides contained a door. Walls and ceiling were painted light buff; floor Indian red; woodwork dark oak.

The apparatus was stationed on a small table placed slightly to one side of the center of the room, so that the electric light sources, which were suspended from the center of the ceiling, were entirely out of view of the observer, while shedding their light over his shoulder onto the test object. The apparatus was placed diagonally to the room, so that light from either window struck the test object at approximately the same angle as the artificial light, and so as to avoid any direct reflection from the observer's eye.

Adjusting and Measuring the Intensities of Illumination

The intensity of illumination on the test-object was regulated by lowering the lamps slightly for the higher intensities, and screening off a portion of their light for the lower intensities, in the case of the artificial light; and by adjusting the opaque shades of the windows by raising them from the bottom, in the case of sunlight.

The intensity of illumination on the test-object was measured with a Macbeth Illuminometer, which is a portable, equality-of-brightness photometer, using a miniature tungsten lamp run from a small storage cell as the standard light-source, a Lummer-Brodhun screen, and producing a balance by moving the standard light. In measuring illumination a disk of opal glass, having the surface sand-blasted, is placed on the given surface, and the brightness of the plaque balanced against the standard light. In measuring the illumination from mercury vapor light and sunlight, ray-filters were used to bring the color of the standard light to match that of the light measured. The instrument had been recently calibrated by the Electrical Testing Laboratories, New York City, a flicker photometer being used in determining the absorption coefficients of the ray-filters used in measuring mercury vapor light, and sunlight. Ten readings were taken of each intensity with each light, after the final adjustment, and the result was checked by an equal numbr of readings taken at the close of the series of observations.

Method of Carrying out the Experiments

The observer was seated in an arm-chair in front of the special apparatus stationed on the table. By slightly inclining the head the opening in which the test-object appeared was in the direct line of vision, the plane of the paper tape being substantially normal to the visual axis. The observer was instructed to adjust the distance from his eyes to the object for the clearest vision, which was done unconsciously after he became accustomed to the work. The electric key with which he registered his reaction was in the position at which his right hand would naturally rest when his arm was supported on the arm of the chair. It required a force of 200 gms. exerted through a distance 0.5 cm. to make contact.

The operator was seated on the opposite side of the table, with the key which controlled the first motion of the shutter within convenient reach, and the opening in which the duplicate numbers on the tape appeared in plain sight. The chronograph and clock were on a table at the side of the room, convenient to the operator, and connected to the apparatus electrically by a piece of flexible bell-wire. The voltmeter and ammeter were on the apparatus table, to which the rheostat was also attached, all within easy reach of the operator. The paper tape was passed under the shutter by being rolled from one drum to another by means of hand wheels at the side of the apparatus, convenient to the operator's left hand, and the shutter was set by being pushed back to its original position, in which it was held by a latch.

The illumination having been adjusted according to the prescribed conditions, the chronograph and clock were set in motion, with both pens in contact with the record paper on the cylinder. The observer was instructed that a succession of printed numbers would appear in the opening in the center of the board, and that as soon as he identified a number he was to press the key at his right hand, afterward repeating the number, so that the operator could check it against the duplicate number appearing at the back of the apparatus, thus making sure that it had been actually identified. The front-board of the apparatus covered the larger part of the visual field of the observer during his observations, thus insuring uniformity of contrast with the test-object, and entire absence of glare. All in readiness, the operator pressed the key, the shutter moved into its position with the opening disclosing a number on the tape; the observer identified the number, pressed the key which released the shutter so that it eclipsed the number, and repeated the number observed. The operator then reset the shutter, turned the tape-drums sufficiently to bring another number into

position, and the observer repeated his operations. This was continued until all the numbers on the tape had been identified by the observer.

Observers

In all, 5 observers were used. The first experiments were made with the 3 different lights, at a uniform intensity of 5 foot-candles, with all 5 observers. These initial experiments were considered rather as qualitative, to ascertain if any appreciable differences in reaction-times would appear, and if so, with what consistency of results. The results proving entirely satisfactory on this point, two of the observers were dropped in the remaining experiments, and their observations at this intensity were omitted from the final calculations. The results of their observations showed the same consistency in their averages and mean variations as those of the other observers in subsequent work.

The 3 observers used were all men, of various ages and vocations as follows: B, age 34, accountant; J, age 29, stenographer; O, age 54, salesman. All wore glasses during the observations.

Method of Measuring the Reaction-Time

The elapsed time between the presentation of the stimulus and the completion of the reaction is represented by the distance between two successive lateral movements of the pen on the chronograph record. The sum of 100 of these distances, representing a set of 120 observations less the first 20, was obtained by adding the individual distances mechanically by means of a a pair of dividers, the successive spaces being laid off along a line on a tape of paper.

The linear distance corresponding to 1 sec. of time was determined by taking the length of a line on the record traced during 10 min., as indicated by a stop-watch, and dividing it by 600. This distance (slightly over 1 in.) was used as the unit for making a scale by which the reaction-times, in the form of linear distances, were measured. The length of the line representing 100 observations, measured by this scale, thus gave the average reaction-time in sec. when divided by 100.

Method of Computing the Mean Variations

An apparatus was constructed, which consisted of a board 30 in. long and 4.5 in. wide, supported at an angle of 45° on a baseboard. A ledge was provided running lengthwise along the center of the board, and a piece of adding machine tape (white paper 2.25 in. wide) was stretched along the upper half, resting against the ledge, upon which was laid the scale of seconds. A slide having its edges perpendicular to the ledge was provided,

which could be moved along over the paper. A slat was attached to the front edge of the baseboard, which was beveled to 45°, which served to hold the chronograph records in place when passed under it, and afforded an accurate guide for the divider points in taking off the distances. A pair of proportional dividers was used, the short and long legs having a ratio of 1.4.

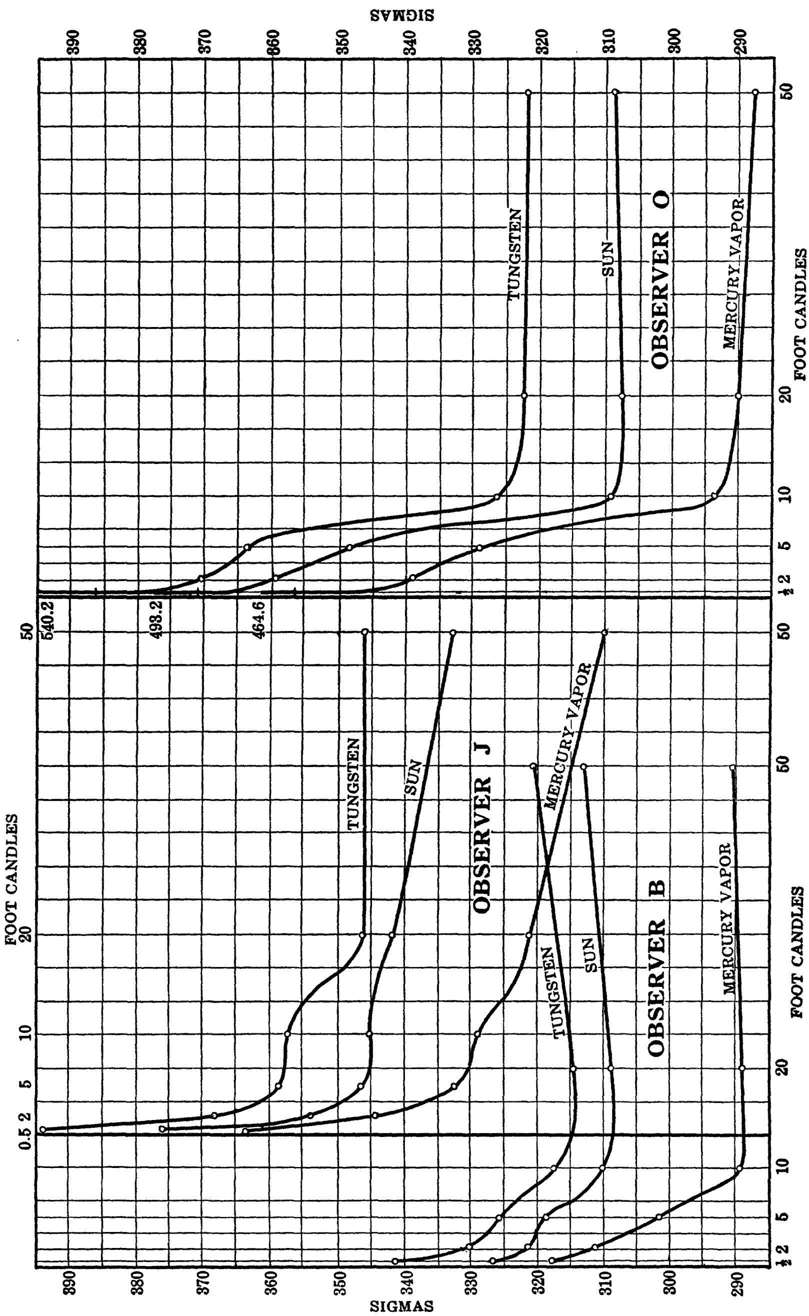
Setting the edge of the slide at the 0 mark on the left of the scale, the distance representing one reaction-time on the chrongraph record was taken off with the short legs of the dividers, and pricked off along the lower edge of the tape, the slide being moved along the distance thus laid off. The distance between the points of the long legs of the dividers was then pricked off along the edge of the slide, perpendicular to the length of the tape. The second reaction-time was then taken off, added to the first in the usual manner, the slide moved up, and the vertical distance laid off against the slide as before; and so on for 100 observations. The total time was then measured on the scale of seconds, and the result, when pointed off, gave the average time in sigma.

Setting the short legs of the dividers to a distance representing this average time, the distance between the points of the long legs was used to set the 0 point on a small movable scale attached to the edge of the slide. The distance of any given point laid off along the slide from this mean value corresponding to the 0 mark on this scale represented the variation of that reaction-time from the mean. The sum of these variations was obtained by moving the slide the length of the tape, reading the distances of the points in like manner, and adding the scale readings. The total thus obtained was a linear quantity, and was reduced by the dividers, measured by the seconds scale, and pointed off for sigma, which gave the mean variation for the set of observations.

Number and Arrangement of Experiments

Six series of experiments were made at intensities of 5, 10, 20, 50, 2, and 0.5 foot-candles, in the order given. In each series results were obtained by 3 observers under the light of tungsten, mercury vapor and the sun. At 5 foot-candles 2 observers took 500 observations under each light; one took 300. At 10 foot-candles all 3 observers took 500 observations; at 20 foot-candles all 3 took 300; at 50 foot-candles all 3 took 300; at 2 foot-candles all 3 took 500, and likewise at 0.5 foot-candle.

Each series of experiments consisted of 120 observations made under each of the three kinds of light at the same intensity, by a single observer at a given sitting. The order in which the different lights were used was rotated in the different series. Practice series were taken until the m. v. of any set of observations was 10% of the average, or less.



CHARTS I, II, III

TABLE I

Visual Cognition Times under 3 types of illumination, at 6 intensities. Averages and mean variations

	Series 6 ½ foot-candle		Series 5 2 foot-candles		Series 1 5 foot-candles		Series 2 10 foot-candles		Series 3 20 foot-candles		Series 4 50 foot-candles	
	AVERAGE	MV	AVERAGE	MV	AVERAGE	MV	AVERAGE	MV	AVERAGE	MV	AVERAGE	MV
OBSERVER B												
Hg	318.4	31.42	311.2	25.98	301.8	21.30	289.8	18.00	289.3	17.80	290.3	18.90
S	326.8	35.02	321.6	24.62	318.5	23.50	309.8	19.60	309.0	19.30	313.3	23.70
T	340.8	36.94	334.8	27.28	330.6	22.50	316.2	21.10	314.6	22.20	320.6	24.10
OBSERVER J												
Hg	363.6	30.96	344.8	27.84	332.3	20.93	329.0	22.10	321.3	18.80	310.0	18.40
S	375.2	30.82	354.4	27.46	346.0	22.60	345.0	25.06	341.6	19.00	333.3	18.30
T	394.0	36.14	367.6	29.12	358.7	24.40	356.2	26.30	345.6	19.10	345.6	18.30
OBSERVER O												
Hg	464.6	56.74	338.4	27.50	327.2	25.60	293.6	20.50	290.0	16.80	288.0	17.40
S	493.2	71.42	359.0	32.30	347.5	29.62	309.2	20.60	307.6	18.40	309.3	19.30
T	540.2	65.12	369.2	31.90	362.2	29.14	326.0	25.20	322.3	25.10	321.6	20.20

In order to afford a "warming up" process before each set of observations, 120 reactions were taken, of which the first 20 were omitted in the calculations. The different series of experiments using different intensities of illumination were taken at widely separated times, extending over a period of 9 months.

Results

The general averages and the mean variations of the cognition times, under the 3 lights at the 6 different intensities, are given in Table I. The curves of the general averages of the 3 lights at the 6 intensities are given in charts I, II, and III, the illumination in foot-candles being plotted as abscissae, against time in sigma as ordinates.

TABLE II

The Difference, the Probable Error of the Difference,[16] and the Probable Correctness of the Difference,[17] between the Average Reactions under Mercury Vapor Light and Sunlight at 6 Intensities of Illumination

Intensities of Illumination	Observer B Dif.	P. E.	P. C.	Observer J Dif.	P. E.	P. C.	Observer O Dif.	P. E.	P. C.
½ foot-candle	8.4	1.777	99.90	11.6	1.620	100.00	38.6	3.470	100.00
2	10.4	1.356	100.00	9.6	1.484	100.00	20.6	1.605	100.00
5	16.7	1.202	100.00	13.7	1.502	100.00	20.3	1.513	100.00
10	20.0	1.013	100.00	16.0	1.263	100.00	25.6	1.098	100.00
20	19.7	1.283	100.00	20.3	1.304	100.00	17.6	1.215	100.00
50	23.0	1.479	100.00	23.3	1.266	100.00	21.3	1.270	100.00

TABLE III

The Difference, the Probable Error of the Difference, and the Probable Correctness of the Difference, between the Average Reactions under Mercury Vapor Light and Incandescent (Tungsten) Light, at 6 Intensities of Illumination

Intensities of Illumination	Observer B Dif.	P. E.	P. C.	Observer J Dif.	P. E.	P. C.	Observer O Dif.	P. E.	P. C.
½ foot-candle	22.4	1.832	100.00	30.4	1.769	100.00	75.6	3.266	100.00
2	23.6	1.428	100.00	22.8	1.524	100.00	30.8	1.593	100.00
5	28.8	1.171	100.00	26.4	1.567	100.00	35.0	1.431	100.00
10	26.4	1.052	100.00	27.2	1.298	100.00	32.4	1.227	100.00
20	25.3	1.390	100.00	24.3	1.307	100.00	32.3	1.474	100.00
50	30.3	1.499	100.00	35.6	1.266	100.00	33.6	1.303	100.00

TABLE IV

Ratios of the Cognition-Times under 3 Types of Illumination at 6 Intensities.

Intensities of Illumination	B Hg	B S	B T	J Hg	J S	J T	O Hg	O S	O T
½ foot-candle	1.000	1.226	1.070	1.000	1.033	1.083	1.000	1.061	1.162
2	1.000	1.033	1.075	1.000	1.027	1.066	1.000	1.060	1.091
5	1.000	1.055	1.095	1.000	1.041	1.079	1.000	1.062	1.107
10	1.000	1.069	1.091	1.000	1.048	1.082	1.000	1.053	1.112
20	1.000	1.068	1.087	1.000	1.063	1.075	1.000	1.060	1.111
50	1.000	1.078	1.104	1.000	1.075	1.114	1.000	1.073	1.116

The reactions taken under mercury vapor light are shorter than those under sunlight, and those taken under sunlight are shorter than those under tungsten light. This relation is constant for all 3 observers at all 6 intensities, though the amount of difference as shown in Tables II and III varies with the light and with the intensity. It will also be seen that, in general, the reactions decrease in length as the illumination increases in intensity; this relation is true for all observers and all lights to an intensity of 20 foot-candles. From 20 to 50 foot-candles under tungsten light the reaction-time for one observer increases, one remains the same, and with one it decreases very slightly. Under sunlight the reaction-time of two observers increases; with one it decreases. Under mercury vapor light the reaction-time of one observer increases very slightly; with two it decreases.

Tables II and III show the difference between the averages of the cognition-times taken under mercury vapor light and sunlight and the difference between the average under mercury vapor light and tungsten, respectively, at the 6 intensities of illumination used, also the probable error of the differences, and the probable correctness of the differences between the sets of cognition-times. The probable errors are small (except in the case of observer O at 0.5 foot-candle, where the m. v.'s were exceptionally large, as were also the differences). The probable correctnesses are either a mathematical certainty, or approach the limit.

Table IV shows the ratio of the differences in time under the 3 lights at each intensity. These differences are smallest at the lowest intensity, and in general tend to increase with the intensity.

Sources of Error

Instrumental Errors include the following:

(1) Variation in rate of revolution of chronograph cylinder
(2) Error in linear distance representing 1 sec. of time
(3) Error in scale of sec. by which reaction-times were measured
(4) Variation in speed of shutter

Accidental Errors include:

(5) Errors in setting the divider points in taking linear distances
(6) Errors in reading the variations in reaction-time on the scale
(7) Errors in making photometer readings

Psychological Errors could arise from the following:

(8) Fatigue
(9) Visual adaptation
(10) Prejudice
(11) Physiological indispositions
(12) Practice
(13) Distractions

These sources of error will now be considered in detail.

(1) One revolution of the cylinder recorded 28 oscillations of the pendulum, which were shown on all records as taken as a check on the regularity of motion of the chronograph. Measurements of the distance between these 28 beats on all records taken showed a mean variation of 0.24 of 1%, and a probable error of .01 of 1%. Applied to the maximum and minimum average times this would give probable errors of .054σ and .028σ respectively.

(2) The results of 3 measurements of the number of pendulum beats recorded in 10 min. gave a m. v. of 0.21 of 1%, and a probable error of 0.625 in the unit of length representing 1 sec. on the scale. As before stated, this being a constant error, and therefore not affecting the differences, no special effort was made to reduce it.

(3) This is subject to practically the same conditions as (5): but the errors were constant as affecting the final results.

(4) This was not measured, as it was sufficiently rapid to produce instantaneous appearance of the stimulus, so far as visual perception is concerned.

(5) The error of a single setting of the dividers was within 5%. The reduction of this error by the canceling out of + and — errors in the 100 settings must bring it near the 0 point on the probability curve; so that the error in the average time was well within the limits of instrumental error.

(6) The same general conditions apply as in (5).

(7) The m. v. in reading photometer settings was 5%. Since the variation in reaction-time due to difference in intensity of illumination was relatively small, the errors in photometric readings are negligible.

In general, it would appear that the mechanical and personal errors of measurement, at least the variable errors which affect the significance of the results, are no greater than—probably not as great as—would have resulted from the methods and apparatus more commonly used for such experiments. There is no doubt that the labor of calculation was much less, and practically free from clerical error.

(8) Care was taken to avoid fatigue by giving rest-periods of 5 to 7 min. between the sets of observations, and two periods of two min. each during the observations. A comparison of the first 10 observations with the last 10 in a representative number of cases showed no discrepancies in average reaction-time, thus proving the absence of fatigue.

(9) The observers were in the room under the adjusted illumination from 5 to 10 min. before beginning their observa-

tions, in the case of the higher intensities, and longer at the lower intensities. The first 20 observations were omitted in the calculations to allow further for adaptation and practice. The comparison of times at the beginning and end of sets of observations, as mentioned in (8), applies equally in this case.

(10) Preference for any one kind of light might affect results; but in this case the effects would necessarily be very marked, and would undoubtedly appear as wide and erratic differences in the reaction-times. The fact that no such fluctuations appeared, but on the contrary the recorded times show a remarkable consistency, is sufficient evidence that they were not subject to the influence of prejudice.

(11) The observers were all in apparently normal health and spirits when making the observations. Furthermore, each observer made observations on 5 different days for each intensity, except the two highest, for which they made observations on 3 different days. The observations at the different intensities extended over a period of 9 months. The total results therefore represent an average which eliminates the factor of physiological abnormalities.

(12) The methods used to eliminate errors of practice have already been described.

(13) All points of mechanical impact in the apparatus were padded with piano felt, so that it operated without sensible noise of any kind. The room had no other occupants than the operator and observer during the observations. There was no glare in the field of vision of the observer, either while he was making his observations or during his rest-periods. The ticking of the pendulum, and the slight clicks of the chronograph magnets, were the only sounds in the room. The noises without were such as the observers were accustomed to hear regularly in their routine work.

Discussion of Results

That there would appear a difference in reaction-time between mercury vapor light and continuous spectra light was rather to be expected in view of the fact that monochromatic light increases visual acuity. It has been generally held, at least among illuminating engineers, that this gain in acuity was comparatively little in evidence at the higher intensities, but became appreciable at the lower intensities. It will therefore be a surprise to the practitioners of the applied science of light to learn that the difference in reaction-time between mercury vapor light and incandescent tungsten light increases with the intensity of illumination in two-thirds of the cases, which would seem to establish the rule. It will probably also be somewhat surprising

to learn that there is no appreciable difference in reaction-time between daylight and tungsten light under the same conditions.

Why these differences should exist is a matter for speculation rather than explanation. Until "the enigma of color vision," as Troland aptly puts it, is solved, an ultimate explanation is apparently impossible. We know, however, that vision by white or polychromatic light is a complex process, and that the visual impression received is the resultant of some kind of summation-process taking place either in the retina or at the cortical centers; and it is conceivable that this process requires time for its consummation. Vision by monochromatic light, not being the resultant of a complex stimulus, may therefore require less time. Purely nerve functions can hardly have any part in the phenomena.

The difference in time between daylight and tungsten light is less suggestive of explanation. There are three factors which may enter into the problem: the difference in color of the two lights will produce a slight variation in the contrast between the test object and the field (the figures and the paper); the two lights exert a different amount of energy for a given visible intensity; and the fact that the eye has been developed under daylight conditions may cause it to function more rapidly under such light than under a light differing in color composition. Which of these causes is operative, or whether all have a share in the result, will require special investigation to determine.

That reaction-time diminishes as the intensity of the stimulus increases is a well established fact, with which the results in the present case agree. The intensity of illumination necessary for minimum reaction-time under any given light does not appear to have been quantitatively determined heretofore. Rice proposed to determine the intensity of illumination of continuous spectra light (daylight and incandescent light) required for the "most efficient vision," by which he meant the greatest visual acuity. He states that, of the various uses of artificial light, the most important is that for reading. In view of the use of the artificial light in the industries, this contention can hardly be maintained at the present time. The fact that the best daylight conditions can be fully equalled by artificial light for the performance of manual labor is of such far-reaching importance as to be classed among the revolutionary improvements in industry, comparable with the use of the steam engine for motive power.

Cognitive reaction-time affords the only parallel to actual working conditions where the hand is directed by the eye; and the cases to which this does not apply, at least to a considerable extent, are comparatively few. The intensity of illumination required for minimum reaction-time is therefore the most reliable

guide for determining the illumination intensities required in industrial lighting.

From the results obtained in these experiments it appears that 10 foot-candles is the practical minimum required where sharp visual focussing is necessary, and the best conditions as to contrast in the objects seen, and sources of external disturbance, such as glare, etc., prevail. Rice concludes that "intensities of 8 and 40 meter-candles (practically 1 and 4 foot-candles) constitute approximately the lower and upper limits respectively of suitable illumination for ordinary purposes." These are much too low for industrial purposes, as the present experiments show, and as recent observations under practical factory conditions corroborate.

Conclusions

(1) Continuous spectra light produces a lag in cognitive reaction-time as comparable with the line spectrum light of mercury vapor of equal intensity.

(2) The light from incandescent tungsten produces a sensible lag in reaction-time as compared with normal white light (daylight, or diffused sunlight) of equal intensity.

(3) The differences in reaction-time, in general, vary directly with the intensity of illumination.

(4) The minimum intensity of illumination required for maximum visual efficiency in reaction-time is between 10 foot-candles and 20 foot-candles.

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[15]Computed by the formulae:

$$\text{P. E.} = \frac{0.8453 \text{ m. v.,}}{\sqrt{\text{n}}} \text{ and P. E. diff. A-B} = \sqrt{(\text{P.E.}_\text{A})^2 \, (\text{P.E.}_\text{B})}$$

[16]Computed by the formula given by Boring. *Amer. Jour. of Psych.*, XXVII, 1916, 315-19.